Chapter V.F. SQUID Detector Design and Performance

Introduction

As outlined in Chapter IV, we propose a novel technique of using SQUIDs to directly measure the precession frequency of the ^{3}He, $v_3 = \gamma_{3He}B_0$, which provides a direct measure of the magnetic field, B_0, averaged over the volume of the cell and the period of the measurement. In addition, appropriately configured SQUIDs could also measure the polarization of the ^{3}He introduced into the cell during the filling period, could monitor the orientation of the ^{3}He magnetization, and could provide a measure of the stability of the magnetic field B_0 in time. The feasibility of using SQUIDs depends on whether the SQUIDs are sensitive enough under the proposed experimental conditions and whether the signal to noise will be adequate.

Experimental Requirements and Considerations

The initial concept for the experiment is that there will be a few SQUIDs, coupled to large-area ($\sim$100cm^2) pick-up coils, to sample the cell volume. This concept is shown schematically in Fig. V.F.1 and described in Chapter V.G. The upper panel of figure V.F.1 shows a finite element method (FEM) model of the experimental set-up as it is currently proposed. The superconducting vessel contains two test cells (upper and lower cylinders) filled with precessing ^{3}He. The pair of coils above and below the test would be connected to SQUIDs. The coils are located away from the test cells to keep them out of the area of high electric field.

The vertically oriented coils will detect the signal from ^{3}He as it is precessing. The horizontally oriented coils will be used to measure the initial ^{3}He magnetization. The SQUIDs will record the change in magnetic field as the polarized ^{3}He are loaded into the cell. This information will enable us to compare the initial magnetization of the ^{3}He before data taking and to reduce any systematic error that might be associated with differing ^{3}He magnetization between runs. These coils will also provide direct information about the presence of any drifts in the magnetic field. The predicted signals for the vertical coils are shown in the lower panel, along with the expected signals without the external superconducting vessel. The peak-to-peak amplitude is $\sim 20\times10^{-18}$ Tm^2 or .01 Φ_0. The model assumes a configuration with parameters as listed in Table V.F.I. The flux coupled to the SQUID is related to the flux in the pick-up coil by the ratio of the SQUID mutual inductance, M, to the sum of the input and pick-up coil inductances (see also chapter V.H).

$$\Phi_s = \frac{M\Phi_p}{(L_p + L_i)}$$

Using typical values of M = 10 nH and (Lp + Li) $\approx$ 1 µH for a large area pick-up coil, the value of flux we expect at the SQUID is $\sim 10^{-4}$ Φ_0. The "typical" noise value from a commercial LTS SQUID [1] at 4 K is N$_{SQUID}$ $\sim$ 5 µΦ_0/Hz$^{1/2}$. We expect an additional

decrease in SQUID noise as it scales as $T^{1/2}$. The following sections report on experimental work with a large coil to measure the noise level and on measurements of the temperature dependence of the noise. Although the signal increases with coil size, there are also problems associated with large pick-up coils in terms of vibration and other noise mechanisms, which could be avoided by using smaller area pick-up coils. The analysis of Chapter V.H concludes that for a smaller coil the expected signal is $\Phi = 7.2\ A_p\ \mu\Phi_0$, where A_p is the area of the coil in cm^2. This implies that adequate signal can be obtained with much smaller coils than in the initial concept.
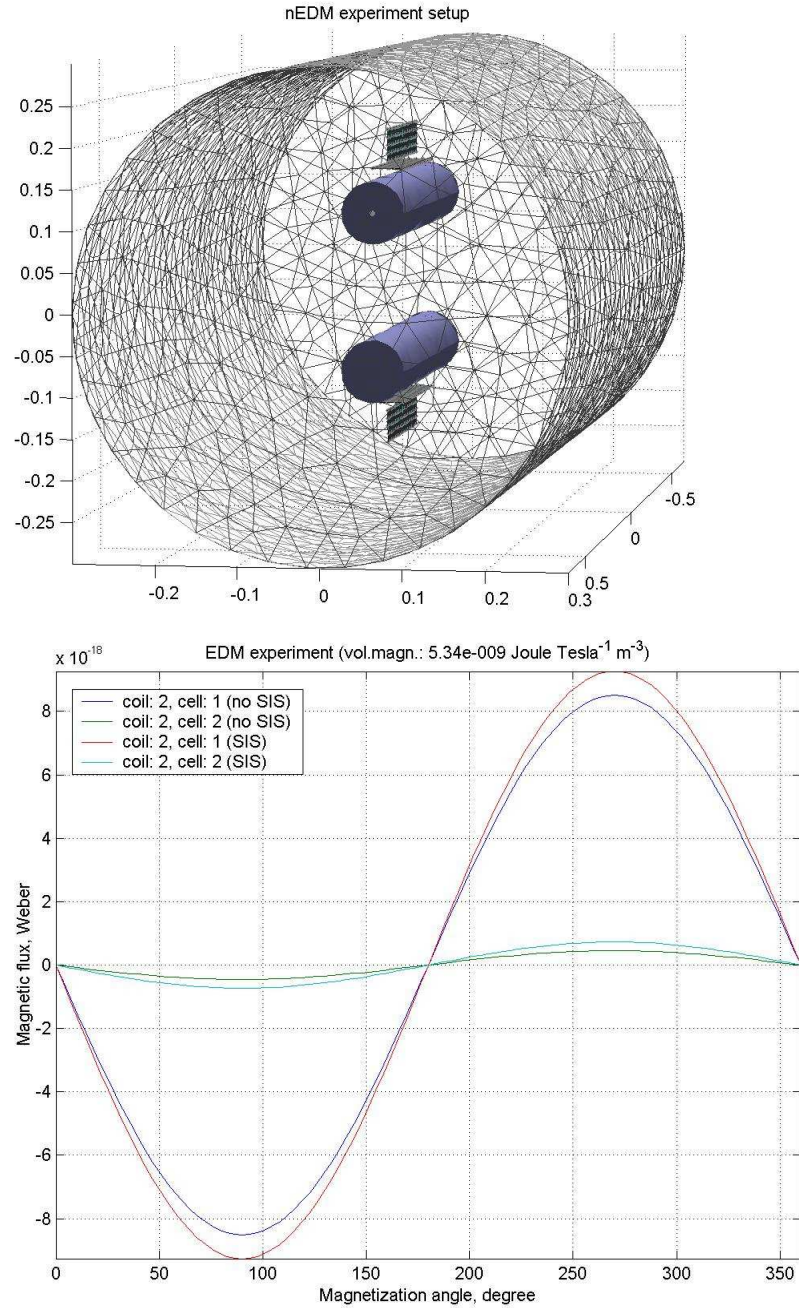

Figure V.F.1. Upper panel: FEM model of the superconducting vessel, EDM test cells, and SQUID pick-up coils. Lower panel: Predicted values of flux in the vertically oriented pick-up coils expected, both with and without the superconducting vessel.

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Table V.F.I Parameters for FEM

Parameter	Value
SIS Cylinder	
Length	1.34 m
Radius	0.3 m
Target cells	
Length	0.5 m
Inner Radius	0.04 m
Center from SIS axis	+/- 0.1 m
Magnetization	$5e^{-9}$ J/(Tm^3) assuming $1.25e^{15}$ 3He/cell
SQUID pickup coils	
Length	0.25 m
Width	0.04 m
Center from SIS axis	
Coils #1,3 (Horizontal)	+/- 0.145 m
Coils #2,4 (Vertical)	+/- 0.175 m

Superconducting test cell

To investigate whether or not we could achieve the desired SQUID noise level, $N_{SQUID} \sim 5\ \mu\Phi_0/\text{Hz}^{1/2}$, with the large pick-up coils attached, we built a lead test cell 8 in. in diameter and 4 in. high that resembled the proposed EDM apparatus. We then carried out a series of experiments [2] that achieved a noise level of $\sim 15\ \mu\Phi_0/\text{Hz}^{1/2}$ at 10 Hz, the expected amplitude of the ^{3}He precession signal. We noted that, despite the large superconducting shield, at frequencies below 100 Hz we still observed noise from vibrations and external sources in the laboratory, implying that great care will be required to shield the system and prevent the large pick-up coils from vibrating. The modulation technique of the electronics may also have prevented us from reaching the intrinsic SQUID noise level. This method averages over many working points of the SQUID, not all of them optimal.

Two-Squid readout technique
To improve the noise performance of our system, we developed a two SQUID read-out technique in parallel with the above experiments; the results are also presented in [2]. With the two-squid (picovoltmeter) system we measured a noise power spectrum with a white noise level of $3\ \mu\Phi_0/\text{Hz}^{1/2}$ down to frequencies ~1 Hz, which is a factor of 5 improvement
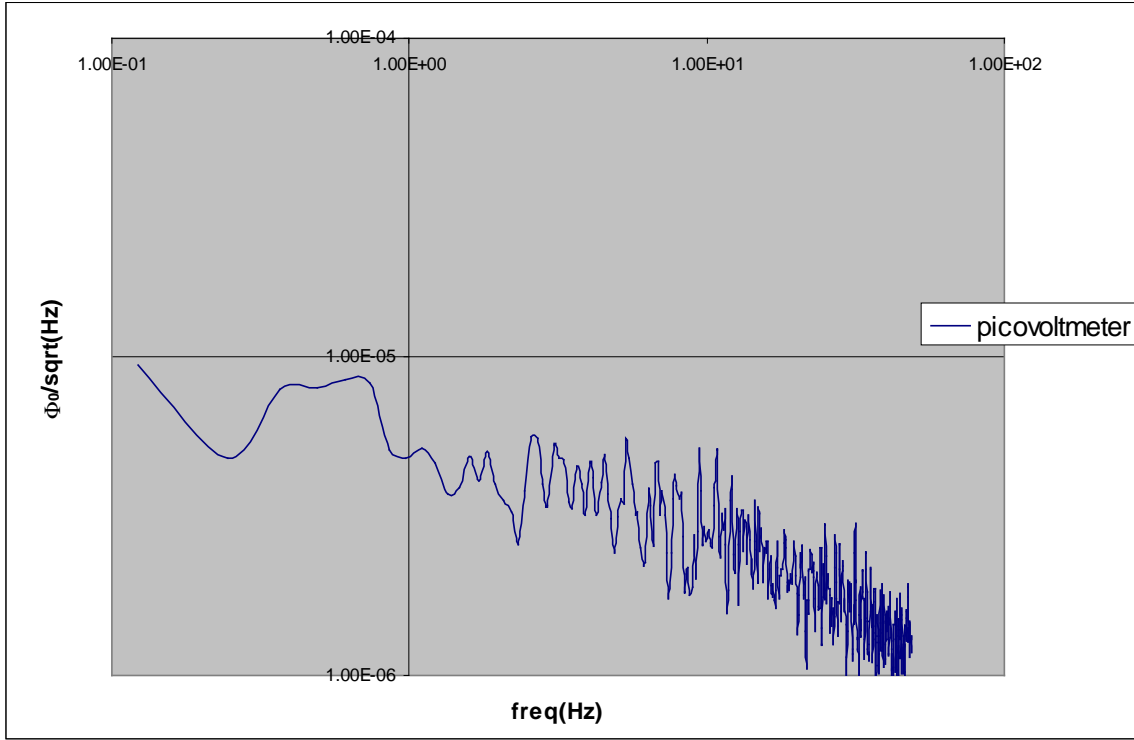
Fig. V.F.2. SQUID noise as a function of frequency. The data were taken with the picovoltmeter inside a superconducting shield and a small-area pick-up coil with the same inductive load as the large-area coil (see text). At the frequency of interest, 10 Hz, the noise was 3 $\mu\Phi_0$/Hz$^{1/2}$

over that achieved with the conventional magnetometer in the lead test can. This white noise level was achieved at lower frequencies due to the better shielding of the probe and because we used a smaller area pick-up loop. The loop provided the same inductive load as the large-area coil, ~1.4 µH, but was much less sensitive to ambient noise. Figure V.F.2 shows the results of the picovoltmeter noise measurements. The issue of the coupling of ambient noise to the SQUIDs when they are connected to the large-area pick-up coils still needs to be fully addressed, and will be re-visited in our discussion of noise sources.

Studies of Temperature Effects

Because of the importance of achieving the predicted noise behavior, we undertook a series of tests of the effects of temperature on SQUID noise. Previous studies of SQUID noise as a function of temperature report that white noise scales as $T^{1/2}$ [3,4], but with 1/f noise the behavior with temperature can be very unpredictable [5]. Figure V.F.3 shows a schematic drawing of the picovoltmeter. The experiments were performed at the National High Magnetic Field Laboratory at Los Alamos in a pumped ^{3}He refrigerator able to attain temperatures down to 0.3 K. The picovoltmeter SQUID was located in section of the probe that was maintained at 4 K. The SQUIDs under test were located in the tip, which could range from 4 K to 0.3 K. A superconducting lead shield surrounded both the picovoltmeter and test SQUIDs.

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Noise vs. Temperature Measurements for a Quantum Design SQUID

V-Φ curves at various bias currents were measured for a Quantum Design SQUID (model 50) at temperatures from 0.3K to 4K. These curves were measured both with the input coil open (no load attached to the SQUID) and with a 1 μH pickup coil. We recorded the power spectral density of the SQUID voltage noise at points along the V-Φ curve where the slope of the V-Φ curve, $\Delta V/\Delta \Phi$, was steepest. The SQUID's flux noise was calculated by the formula $N_{SQUID} = V_n(\Delta\Phi/\Delta V)$, where V_n is the measured voltage noise. The noise values recorded were for the white component of the voltage noise. Some of the data summarized below are also presented in more detail in [6].
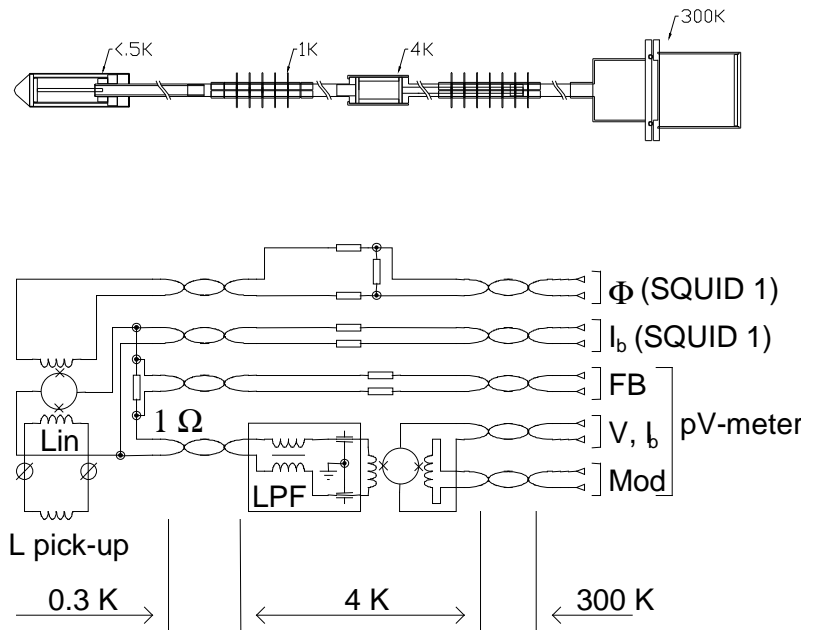
Fig. V.F.3. Schematic drawing of picovoltmeter probe.

We were primarily interested in how the SQUID noise changes as a function of temperature. We expect that the flux noise squared, N_{SQUID}^2, should scale linearly with temperature. In Fig. V.F.4 we show a plot of N_{SQUID}^2 vs. temperature for the SQUID with the pickup coil (upper) and with the input left open (lower). The data are lowest values of N_{SQUID} for each particular temperature. The solid lines are a linear fit to the data, $N_{SQUID}^2 = a \cdot T + b$. The flux-noise energy exhibits the characteristic linear dependence on T, however the slope is slightly different for the two curves. The slope is a = 0.81 for the SQUID with a pickup coil and a = 1.00 for the open SQUID. For the open SQUID the intercept term (excess noise energy at T = 0) is b = 0.08, while for the SQUID with a pickup coil, it is b = 0.61. This excess noise energy behavior has been seen before [6] and was found to be due to either the SQUID chip materials, or the material the SQUID was mounted on. In our case the excess noise is very small for the SQUID with no load. However, when the pick-up coil is attached we see an overall increase in noise. We believe that the greatest contributor to the increased noise is due to Johnson noise from the materials on which the SQUID is mounted, is now being coupled into the pickup coil. At certain frequencies we also saw noise from mechanical vibration. The issue of vibration will have to be a serious consideration in the actual experimental design.

For a comparison of the flux noise from the picovoltmeter technique vs. the conventional modulation readout electronics, we measured the noise at 4 K for both cases, with a pickup coil attached. The noise for the conventional electronics was 3.5 μΦ$_0$/√Hz while for the
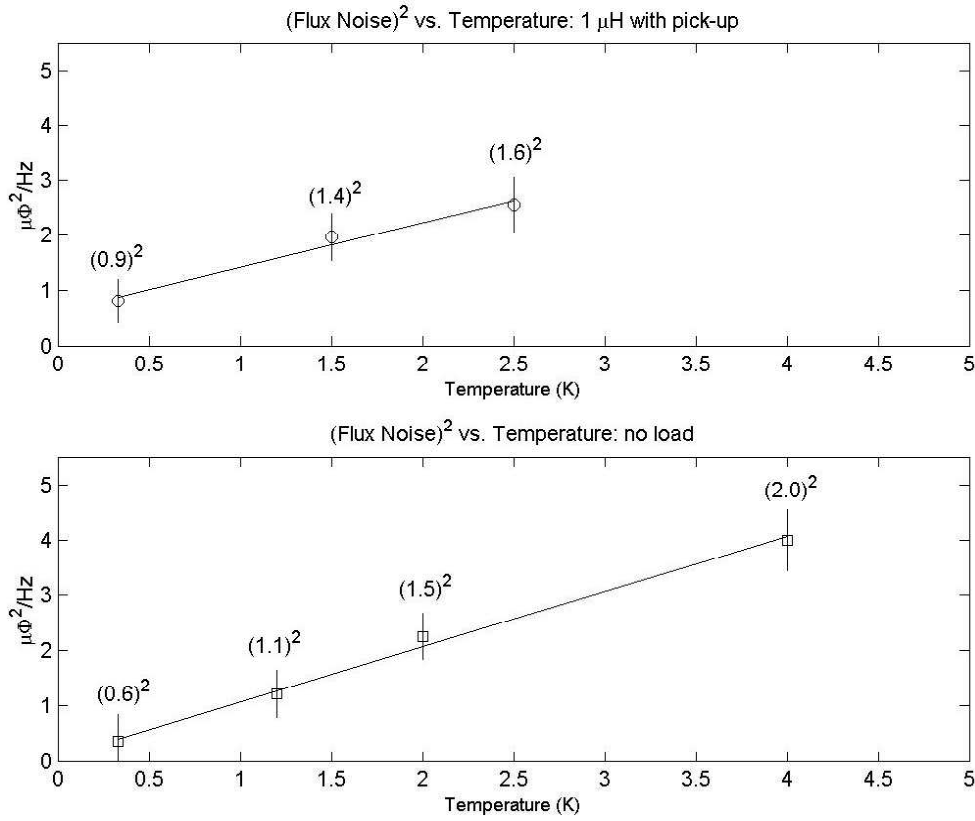
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Fig. V.F.4. Plots of flux noise squared vs. temperature. The data are the best values at each temperature. The solid lines are a fit to the expression $\Phi_n^2 = a \cdot T + b$. Upper: SQUID with a 1 μH pickup coil. Lower: SQUID with no load.

picovoltmeter it was 1.8 $\mu\Phi_0/\sqrt{\text{Hz}}$. It should be noted that this measurement was made on a slightly different probe than the other noise measurements presented.

Noise vs. Temperature Measurements for a Conductus Mag8 Magnetometer

Noise vs. temperature measurements were also made for a Conductus Mag8 magnetometer [1]. The difference between the magnetometer and the Quantum Design SQUID is the area of the pick-up loop. The Quantum Design SQUID is made to attach an external pick-up loop of the user's design such as the 100 cm^2 loop. However, one should note that the effective area of the 100 cm^2 loop is only 100 mm^2 because the coupling is not ideal. The magnetometer has an integrated pick-up loop with an effective area of $\sim$ 2.5 mm^2. The loss in signal would be a factor of 40. However an advantage of using a magnetometer is that with the smaller pick-up loop, the SQUID measurements are less likely to be contaminated by noise due to vibrations. Since the pick-up area is much smaller, one would have to use an array of such devices to achieve the required signal-to-noise for the experiment. Present SQUID systems for brain imaging use arrays of many hundreds of SQUIDs.

The behavior of SQUID noise as a function of temperature for the Mag8 is shown in Fig. V.F.5. The data are still preliminary, but the expected behavior with temperature is again
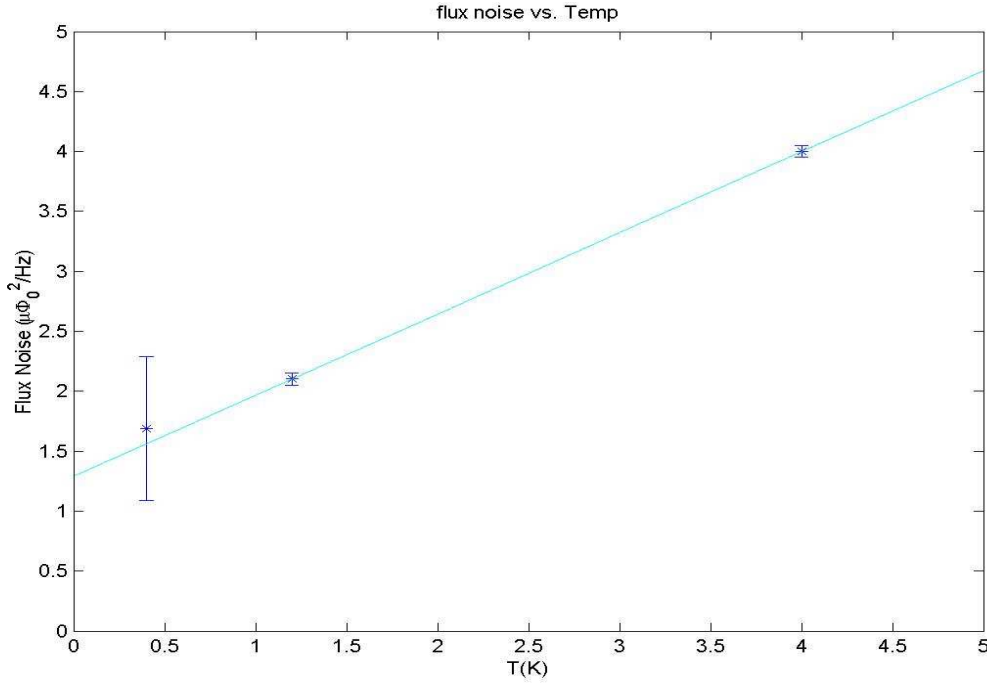

Figure V.F.5. Plots of flux noise squared vs. temperature for a magnetometer. The data are the best values at each temperature. The solid lines are a fit to the expression $\Phi_n^2 = a \cdot T + b$.

seen. The solid line is a best fit to the expression $N_{SQUID}^2 = a \cdot T + b$, with $a = 0.68$ and $b = 1.29$.

External Noise Sources

It is anticipated that the most critical issue for using SQUIDs to measure the ^{3}He precession signal successfully will be keeping noise sources at the frequency of interest to an acceptable level. Experimental noise sources of concern are vibrations of the SQUID pick-up loop in the B_0 field, the magnetic fields due to leakage current from the high voltage plates, Johnson noise from non-superconducting elements, magnetic noise from power lines and electrical equipment leaking into the superconducting shield through penetrations, and non-uniformity in the B_0 field.

To address the issues of noise sources in the experiment, many studies will take place throughout the entire design and development of the EDM experiment. A simple set of experiments to measure environmental noise in the experimental hall were conducted during the run cycle in December 2001. Three HTS SQUIDs were placed in a temporary dewar and background noise levels were measured. This represents a "worst-case" measurement, since the SQUIDs had no shielding and were HTS devices, with inherently

worse noise performance than helium cooled devices. The data are currently being analyzed.

As the design of the cryostat and superconducting shield for the experiment are developed, tests can be conducted to study the effects of penetrations and how to defeat them (i.e. 90^0 bends or other ways to "choke" field before it enters the superconducting vessel). These tests do not require the ultra-low temperature or the presence of the polarized ^{3}He. Tests such as these can be made at every stage of the design of the shield. The effectiveness of different designs of the superconducting shield with penetrations might possibly be modeled using commercially available software such as Elektra [7] or with the finite element model.

Some of the effects of vibration can be tested with the existing lead can developed for SQUID noise measurements. When the coils used to produce the magnetic holding field, B_0, have been built, we can test again. Also, the SQUIDs can be used to test the stability of the field produced by the B_0 coils. We anticipate that if we can use the small area magnetometers, the problem of vibration in an external field will be greatly reduced.

All materials proposed to make the cell can be tested with a simple SQUID set-up to see if they are suitable. The materials can be placed inside the existing lead can and their noise measured by SQUIDs. It is possible to try and calculate the B-fields expected from leakage currents, but they can be measured without beam etc. as soon as the high voltage plates are in place.

Conclusions

Initial work has shown that obtaining SQUIDs with sufficient sensitivity will not be an issue. We have also recently demonstrated that the SQUID noise will scale with temperature as $T^{1/2}$ for a variety of SQUIDs available to us. Thus we expect an improvement in SQUID performance from our laboratory tests at 4 K to the real experiment at 0.3 K. All of our initial work has confirmed our suspicion that ambient noise will be our greatest problem. In particular, vibration appears to be a large problem. One way to mitigate the effects of vibration is to use an array of SQUIDs with small-area pick-up coils instead of a few SQUIDs coupled to large-area coils. The suitability of this technique is currently under study. Another method to reduce ambient noise effects would involve using SQUID gradiometers, this method is also presently being investigated.

Many of the sources of experimental noise that are detrimental to the SQUIDs would need to be addressed anyway in the context of other experimental techniques. In addition, SQUIDs provide many other useful pieces of information to the experiment and its design. SQUIDs can be used to record the initial magnetization (during the fill of the 3He atoms), reducing the systematic error. SQUIDs can be used to keep track of the stability of the magnetic holding field B_0. At many points during the experimental design the SQUIDs can

be used as diagnostics and to provide feedback about suitability of the experimental design.

References

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